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Projected extreme temperature and precipitation of the Laurentian Great Lakes Basin

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ABSTRACT

The Laurentian Great Lakes Basin has been subject to increasingly extreme weather events in the past seven decades. This study uses a regional climate model spanning the region to project summer maximum temperature (Tmax), winter minimum temperature (Tmin), and seasonal extremes of precipitation for the mid-century (2030–2059) and late-century (2060–2089) relative to the baseline period (1980–2009). The basin's southern portion (US side) summer Tmax increases are projected to be greater than those in the northern portion of the basin (Canadian side), whereas Canadian side winter Tmin increases will be greater than those on the US side. The annual number of extremely hot days (Tmax ≥ 32 °C) in this region during mid-century and late century periods is projected to rise by 6.1–15.3 days and 10.0–32.1 days relative to the baseline period (1980–2009) values (0.1–21.5 days), respectively; whereas the annual number of extremely cold days (Tmin ≤ −18 °C) is projected to be reduced by 3.9–6.2 days (mid-century) and 5.5–9.9 days (late century) compared to the baseline period (2.6–60.5 days). The annual number of extremely cold days is projected to remain unchanged in 23%–61% of the area over the Lakes. The Basin's annual precipitation is projected to rise continuously but the degree of change will vary by season. Winter and spring precipitations are projected to rise greatly, autumn precipitation will rise to a lesser extent, but summer precipitation is projected to decline relative to the baseline period. The annual number of extremely wet days (≥ 40 mm/day) over the Lakes only is projected to increase by between 0.3 and 0.6 days (mid-century) and 0.5–0.8 days (late century). The annual number of extremely wet days over land areas is projected to increase by 0.2–0.6 days and 0.5–0.8 days, respectively. However, about 20% of the region will also experience a reduced number of extremely wet days, which implies that future precipitation changes in this region may be quite different at smaller scales (e.g. county to county) than over larger scales. We propose that lake and land differences, seasonal variations, and changed and unchanged areas should all be considered in climate studies of regions within which large inland water bodies reside, as these regions will have similarities with the Great Lakes basin.

1. Introduction

The Laurentian Great Lakes Basin is important to the economies and societies of both the United States and Canada. This region comprises over 20% of the world's surface freshwater (80% of North America's freshwater resources), not only providing drinking water to over 33 million people (10% of the US and 30% of the Canadian population), but also supporting the huge industrial and agricultural sectors of the two countries (Kling et al., 2003; Wuebbles et al., 2010). Historical observations show that the annual number of extreme heat and precipitation events has risen and that frequencies of extremely cold weather events have declined over the past several decades in North America (Peterson et al., 2008). The 1995 heat wave in Chicago, Illinois caused over 700 deaths (Dematte et al., 1998). Increasing air temperature and humidity in the atmosphere have also led to more incidences of heavy precipitation in this region (Kunkel et al., 2003). In contrast, the reduced duration and areal extent of winter ice cover on the Lakes might extend the commercial shipping navigation period (Millerd, 2010) but could also change the distribution of habitat for many fish species (Lynch et al., 2010). Recent studies indicate that 10%–30% of the commercial flights that occur on hot summer days may require weight restriction below their maximum takeoff weights due to the reduced density of warmer air (Coffel et al., 2017). The Great Lakes Basin includes Chicago's O'Hare International Airport and Toronto's

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Pearson International Airport, which are the third-busiest US airport and the busiest Canadian airport, respectively. Future warming in this region may significantly affect commercial flights on extremely hot summer days. Additionally, a previous study (Shrubsole et al., 1993) indicated that flood frequency and the associated damage costs in this region have risen between 1859 and 1987. Evidence from all of these studies suggests that it would be prudent to consider the effects of future changes in extremes of temperature and precipitation of this region.

The PRECIS (Providing REgional Climates for Impacts Studies) regional climate modeling system was developed by the United Kingdom Met Office Hadley Centre (Jones et al., 2004; Massey et al., 2015). It can generate high-resolution climate change information for any region of the world, thus providing detailed projections of climate. PRECIS has been applied to regions throughout the world, many of which encompass large expanses of both land and water including the Caribbean (Campbell et al., 2011), Southeast Asia (McSweeney et al., 2012), and the Mediterranean and Middle East (Constantinidou et al., 2016). Other studies have investigated regions adjacent to large water bodies, such as India (Rao et al., 2014), the Pacific Northwestern United States (Zhang et al., 2009), and the Province of Ontario, Canada (Wang et al., 2014).

In this study, we use PRECIS to dynamically downscale a set of global climate models (Hadley Centre Coupled Model, version 3Q, hereafter HadCM3Q (Wilson et al., 2010)) over the Great Lakes Basin. The objective of this study is to examine changes in future extreme temperature (summer Tmax and winter Tmin) and precipitation in this region.

2. Data and methods

The extreme temperature and precipitation definitions used in this study are taken from several recent studies. Schlenker and Roberts (2009) reported increases in crop yields in the United States as temperature increased up to 29 °C for corn, 30 °C for soybeans, and 32 °C for cotton. However, yields sharply decreased when temperature increased beyond this threshold. Park (2016) studied US county-level payroll data and (excluding agricultural sectors), found that when the United States has one additional day of maximum temperature above 90 °F (32 °C), the country experiences a decrease of 0.048% per capita payroll the subsequent year. Industrial activities such as construction and mining, which are more vulnerable to environmental stress, respond more negatively, with per-day impacts that are 3.5 times larger than impacts to sectors such as financial services, which are less affected by exposure to the elements (0.073% and 0.019% per day if Tmax exceeds 90 °F (32 °C)). The Great Lakes Basin's relative humidity fluctuates ~~by~~ between 66% and 83% over a twelve month period, and summer humidity is generally > 70% (Derecki, 1976), which means that air temperature of 32 °C with 70% relative humidity can be felt subjectively as 41 °C. This relationship is based on the local vapor pressure found in this region (Derecki, 1976). Consequently, we operationally define a temperature of 32 °C or higher as "extremely hot" (Tmax). Similarly, we define a temperature of −18 °C or lower as "extremely cold" (Tmin), which is consistent with previous climate research within this region (Vavrus and Van Dorn, 2010). We set daily precipitation greater than or equal to 40 mm as the threshold definition for an "extremely wet" day because this amount has been observed for fewer than 5% of rainy days in North America in the late 20th century (Vavrus and Van Dorn, 2010; Gao et al., 2012). In addition, we define precipitation of 10 mm/day as being a "very wet" day (in contrast to the 40 mm/day "extremely wet" criterion), because the annual precipitation of this region generally varies between 800 mm/year and 1000 mm/year (2.2 mm/day to 2.7 mm/day).

The extreme climate change variables used in this study include: summer (June, July and August - JJA) Tmax, winter (December, January and February - DJF) Tmin, mean annual number of hot days (Tmax ≥ 32 °C) and cold days (Tmin ≤ − 18 °C), mean annual number of very wet days (≥ 10 mm/day) and extremely wet days (≥ 40 mm/day). We also assess spatial variation - the climate variables' differences over lake versus land areas, and how they change seasonally in this region.

The HadCM3Q Perturbed Physics Ensemble (PPE) of GCMs is a version of the Hadley Centre's third generation coupled ocean-atmosphere general circulation model HadCM3, in which the Great Lakes (and other large inland water bodies, such as Lake Victoria and the Caspian Sea) are explicitly represented by the ocean component of the coupled model (Wilson et al., 2010). This allows the HadCM3Q GCMs to simulate interactions between the atmosphere and surface of the Great Lakes more realistically than using a non-flux corrected GCM alone.

The HadCM3Q PPE contains 17 ensemble members in which the dynamical formulation of the models is the same for all members, but values of 32 atmospheric parameters are perturbed within a range that spans the known bounds of uncertainties for each parameter (McSweeney et al., 2012; Wilson et al., 2010). Member "zero" of the HadCM3Q PPE is referred to as HadCM3Q0 and contains "unperturbed" values of selected physical parameters, acting as a control member. HadCM3Q1, HadCM3Q2, HadCM3Q3 and so on up to HadCM3Q16 GCM models are based on the standard HadCM3Q0 model, but with perturbed values for the identified atmospheric parameters. Thus, HadCM3Q GCMs can quantify uncertainties in, 1) regional climate model results due to uncertainty in driving GCM formulation; and 2) fine-scale climate change due to uncertainties in global and regional model formulation (McSweeney et al., 2012; Wang et al., 2014). The previous studies (McSweeney et al., 2012; Wang et al., 2014) revealed that members HadCM3Q0, Q3, Q10, Q13, Q15 (physical configurations summarized in Table 1) were sufficient to span the range of uncertainties in temperature and precipitation for the Great Lakes region - the member Q0 acts as a control member, while Q3 was the driest member, Q10 was the wettest, Q13 was the hottest and Q15 was the coldest.

PRECIS utilizes the regional climate model HadRM3P, which is a comprehensive model that can represent important physical processes

Table 1
Selected parameters of the five different GCMs physics configurations used in this study.**

	HadCM3Q0	HadCM3Q3	HadCM3Q10	HadCM3Q13	HadCM3Q15
V_{f1} (ms^{-1})**	1	1.32784	0.50546	1.52212	1.71394
C_t (s^{-1})	1.0e-4	0.000337	0.000329	0.000273	7.4e-5
C_w_land (kgm^{-3})	0.0002	0.000169	0.00172	0.000985	0.00017
C_w_water (kgm^{-3})	5.0e-5	4.07e-5	0.00043	0.000246	4.1e-5
Water-ice diffusion coefficient ($m^2 s^{-1}$)	2.5e-05	2.387e-5	2.393e-5	2.433e-5	2.347e-5
Boundary layer flux profile parameter	10	12.4727	8.6838	7.2765	12.8178
Ice particle size (μm)	30	28.249	29.069	33.348	30.078
Charnock constant	0.012	0.0121	0.0157	0.0123	0.0162

** V_{f1} - Ice fall speed, C_t - Cloud droplet to rain conversion rate, C_w - Cloud droplet to rain conversion threshold, Charnock constant - Roughness lengths and surface fluxes over water. More details of other parameters can be found in Murphy et al. (2004) and Collins et al. (2006).

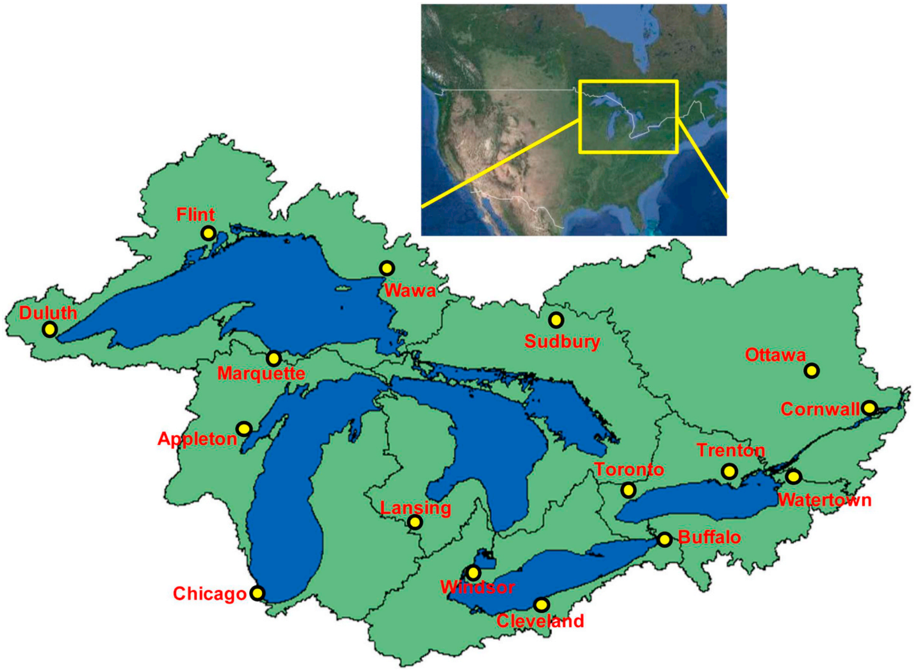

Fig. 1. The study area of the Great Lakes basin and the sixteen stations selected for data validation.

within the climate system, such as dynamic flow, the atmospheric sulfur cycle, clouds and precipitation, radiative processes, and the interactions between land surface and deep soil (Jones et al., 2004; Massey et al., 2015). PRECIS can downscale HadCM3Q GCMs at two resolutions: 0.44 × 0.44 degree (about 50 km × 50 km) and 0.22 × 0.22 degree (about 25 km × 25 km) (Wilson et al., 2010). In this study, we downscaled five GCMs (HadCM3Q0, Q3, Q10, Q13, and Q15) with PRECIS at 25 km × 25 km resolution to project the Great Lakes Basin climate change between 1970 and 2099. We selected a baseline period between 1980 and 2009 for PRECIS performance validation and used two 30-year future periods [mid-century (2030 to 2059) and late century (2060 to 2089)] for climate projections.

3. Data validation

To validate the performance of PRECIS downscaling, we chose eight Canadian weather stations and eight US weather stations (Fig. 1; Table 2) from the two countries' long-term weather observation networks. We obtained daily climate data from the 16 stations for comparison with the PRECIS results generated over the same baseline period (1980–2009). The locations of the 16 stations encompassed the whole basin and were situated on land areas adjacent to lakes (Duluth MN, Flint ON, Chicago IL, Toronto ON, Cleveland OH, etc.) and the bordering landmass of the lakes (Lansing MI, Sudbury ON, Ottawa ON, etc.), allowing us to assess the models' performance (five GCMs downscaled by PRECIS) in capturing spatial variation across this region.

Comparisons of observed values and the five model simulations for summer Tmax (mean annual number of extremely hot (≥32 °C) days), and winter Tmin (mean annual number of extremely cold (Tmin ≤ − 18 °C) days) for the 16 weather stations are summarized in Tables S1 and S2, respectively. Comparisons of observed and simulated annual precipitation (the annual number of very wet days (≥10 mm/day) and extremely wet days (≥40 mm/day)) are presented in Table S3. The five-model mean Tmax and Tmin biases (i.e. differences between the model results and the observational data) over the 16 stations varied between −3.0 °C and 5.0 °C (Table S1) and − 0.4 °C to 5.8 °C (Table S2), respectively. Furthermore, the smallest Tmax and Tmin biases (within the five simulations) only accounted for −0.9 °C to 0.6 °C (Table S1) and − 0.4 °C to 3.7 °C (Table S2), respectively. The smallest biases of yearly hot days (Tmax ≥ 32 °C) and cold days

Table 2
Sixteen weather stations (first 8 from Canada and last 8 from the US) selected for data validation.

Abbreviation	Weather Station Name	Longitude	Latitude	Elevation (m)
Flint	Flint Weather Station, ON	89.68°W	48.35°N	274.0
Wawa	Wawa airport, ON	84.78°W	47.97°N	287.8
Sudbury	Sudbury Weather Station, ON	80.80°W	46.63°N	348.5
Windsor	Windsor Airport, ON	82.95°W	42.28°N	189.6
Toronto	Toronto Pearson Int'l Airport, ON	79.63°W	43.68°N	173.4
Trenton	Trenton Airport, ON	77.53°W	44.12°N	86.3
Ottawa	Ottawa Macdonald-Cartier Int'l Airport, ON	75.67°W	45.32°N	114.0
Cornwall	Cornwall Weather Station, ON	74.75°W	45.02°N	64.2
Duluth	Duluth Int'l Airport, MN	92.18°W	46.83°N	434.9
Appleton	Appleton Weather Station, WI	88.36°W	44.25°N	228.6
Marquette	Marquette Airport, MI	87.55°W	46.53°N	431.3
Chicago	Chicago Midway Int'l Airport, IL	87.77°W	41.73°N	189.0
Lansing	Lansing Airport, MI	84.58°W	42.78°N	256.3
Cleveland	Cleveland Hopkins Int'l Airport, OH	81.87°W	41.42°N	237.1
Buffalo	Buffalo Niagara Int'l Airport, NY	78.72°W	42.95°N	214.9
Watertown	Waterdown Airport, NY	76.02°W	44.00°N	96.9

Table 3
The data validation comparisons (biases that “simulated result” minus “referred data”) between this study and recent Great Lakes basin climate studies. “Sta_obs” means the station historical weather observation dataset.

Study	GCMs	Downscaling method	Resolution	Studied area	Referred data	Compared period	Compared data scales	Model biases (“Simulated result” - “published data”)			
								Summer Tmax (°C)	Winter Tmin (°C)	Precipitation (cm/year)[c]	Extreme wet days
This study	HadCM3Q series (Q0, Q3, Q10, Q13, Q15) GFDL, HadCM3,	dynamical (WRF)	$25 \times 25\ km^2$	16 cities	Sta_obs	1980–2009	Point to point[a]	−0.9 to 0.7	−0.4 to 3.7	−1.4 to 38.7	−0.03 to 1.47
				16 cities	Sta_obs	1980–2009	Mean 16 sites[a]	0.2	1.2	−8.5	0.38
				CA 8 cites	Sta_obs	1980–2009	CA 8 sites[a]	0.2	1.2	−0.4	0.35
				US 8 cites	Sta_obs	1980–2009	US 8 sites[a]	0.1	1.2	9.6	0.4
Vavrus and Van Dorn (2010)		Statistical (mean of 3 GCMs)	Point	Chicago	Sta_obs	1980–2010	Point to point[a]	0.7	0.4	0.9	0.17
	PCM			Chicago	Sta_obs	1961–1990	Point to point	1.0	0.3	n/a	−0.18[b]
Gao et al. (2012)	CESM 1.0	Dynamical (WRF)	$4 \times 4\ km^2$	Michigan	NCDC	2001–2004	State	1.93	n/a	6.48	0.8
	CESM 1.0	Dynamical (WRF)	$4 \times 4\ km^2$	Ohio	NCDC	2001–2005	State	0.68	n/a	8.54	1.2
	CESM 1.0	Dynamical (WRF)	$4 \times 4\ km^2$	New York	NCDC	2001–2006	State	0.78	n/a	2.31	0.1
Gula and Peltier (2012)	CCSM3	Dynamical (WRF)	$10 \times 10\ km^2$	GLs basin	CRU	1979–2001	Broader GLs basin	± 1.26	± 1.20	± 0.3 mm/day[d] = ± 10.9 cm/year	n/a
D'Orgeville et al. (2014)	CCSM3	Dynamical (WRF)	$10 \times 10\ km^2$	GLs basin	CRU	1979–1994	Broader GLs basin	Tmean[b] = −1 to −2		± 0.5 mm/day[d] = ± 18.3 cm/year	n/a
Notaro et al. (2015)	MIROC5	Dynamical (RegCM4)	$25 \times 25\ km^2$	GLs basin	UOD	1980–1999	Broader GLs basin	Tmean[b] = ± 1.9		± 0.29 mm/day[d] = ± 7.7 cm/year	n/a
	CNRM	Dynamical (RegCM4)	$25 \times 25\ km^2$	GLs basin	UOD	1980–2000	Broader GLs basin	Tmean[b] = ± 1.16		± 0.45 mm/day[d] = ± 16.4 cm/year	n/a

Note: The names of GCMs, RCMs and published data (NCDC, CRU, UOD) in this table are abbreviated, due to limited space here. These abbreviations are commonly used in climate studies, and details can be found in the references and our study (HadCM3Q and PRECIS).

Underlined data values are means of certain entries (broader-scale data.) The calculated biases for these entries are small because an influence of some extreme biase values may be modulated by the large number of small biases values included in the average.

[a] The study model biases shown in this table are the least-biased simulated results. Details can be found in Tables 1, 2, 3.

[b] The extreme wet day bias in reference (Vavrus and Van Dorn, 2010) represents the precipitation > 50 mm/day, but our extremely wet day in our study is defined as ≥40 mm/day.

[c] Precipitation data units shown in references were mm/day. For comparability, the data are expressed as cm/year in this table. The precipitation bias of 38.7 cm/year only occurred at the point of Watertown.

[d] No Tmax or Tmin data were reported in the references, instead, we cited the Tmean values here.

(Tmin ≤ −18 °C) ranged from 0.0 days to 12.6 days (Table S2) and − 24.2 days to −0.6 days, respectively. The greatest annual precipitation simulation biases varied from −6.2 to 4.1 cm/year (percentile biases only account for 0.004% to 6.8%) for 13 of 16 stations except for Lansing, Cleveland and Watertown (Table S3). The very wet day (≥10 mm/day) and extremely wet day (≥40 mm/day) biases are also in general agreement with the observations. Chicago's simulated very wet days and Marquette's simulated extremely wet days corresponded almost exactly with observed data. All of these point-to-point data validations indicate that PRECIS simulations can perform very well in capturing the baseline temperature and precipitation of the Great Lakes Basin. Point to point data validations may yield gaps at some sites, but the overall performance of the simulation should be considered on a large scale as in previous studies (Vavrus and Van Dorn, 2010; Wang et al., 2014). The data validation results from this study can be compared to the statistical point to point downscaling of Chicago's climate study (Vavrus and Van Dorn, 2010) and other dynamical downscaling studies of this region (Gula and Peltier, 2012; Notaro et al., 2015).

In Table 3, we collected recently published climate simulation data validations that focused on (or involved) this region. The data validation biases in this study are comparable to (or smaller than) recent studies despite the use of different downscaling methods (statistical and dynamical) (Vavrus and Van Dorn, 2010; Gao et al., 2012; Gula and Peltier, 2012; D'Orgeville et al., 2014; Notaro et al., 2015). The observed historical data from 16 stations indicate that the climate patterns stem from complex land-lake interactions. As such, we view the modeling framework used in this study as an especially appropriate method of accurately simulating regional Tmax and Tmin variations. The reason for this is that the data from the lakes are internally consistent within the GCMs by virtue of the fact that climate data over the Great Lakes are explicitly downscaled from the GCMs inside water model components.

Additionally, these results also demonstrate that the climate projections with HadCM3Q GCMs and PRECIS, which consider land and lake data in a single RCM may be as or more effective than previous projections that consider land and lake data from quite different land and lake RCM models (Gula and Peltier, 2012). This is because a crucial factor in climate projections of the Great Lakes basin (and other regions that involve land and large water bodies) is to accurately simulate the interactions between lakes and land areas (as opposed to considering lakes and lands separately). Values of water surface temperature and water ice fraction are provided to the PRECIS as surface boundary data (Wilson et al., 2010), which avoids the problem of model compatibility between the lake model and the land model (with differing formulations).

4. Future extreme climate projection

Given that global climate change is a dynamic process, and no single GCM model can perform much better than other GCMs across all regional climate simulations (Sheffield et al., 2013), the ~~use~~ of five GCMs in this study allows for uncertainties in future projections to be adequately captured and thus they provide a relatively comprehensive estimate of projected temperature and precipitation extremes in the Great Lakes Basin. The projected changes in mid-century and late century extreme temperatures (summer Tmax and winter Tmin) and the numbers of extreme temperature days (hot days (Tmax ≥ 32 °C) and cold days (Tmin ≤ − 18 °C)) are illustrated in Figs. 2 and 3, respectively, and summarized in Table 4. Mid-century temperatures (summer Tmax and winter Tmin) show an increase from 1.5 °C to 4.0 °C grid cell to cell, and late century changes will be higher, increasing by between 3.0 °C and 8.0 °C (Fig. 2). Projections indicate that the entire regional mid-century summer Tmax and winter Tmin increases average by 2.5 °C to 3.5 °C and by 2.4 °C to 3.4 °C, respectively, while the increases in late century summer Tmax and winter Tmin are 3.5 °C to 5.9 °C and 4.3 °C to 5.9 °C, respectively (Table 4). Summer Tmax and winter Tmin in this region are generally projected to consistently increase throughout the mid-century and late century. However, the degree of future temperature increases will differ between Canada and the US. Specifically, the southern portion of the region (US side) will be subject to greater increases in Tmax than the northern portion (Canadian side); in contrast, the winter Tmin increases will be greater in the northern areas than the south (Fig. 2). Thus, increases in summer warming will be greatest in southern portions of the Great Lakes basin whereas the frequency of extremely cold winter events will be most reduced in the northern portions of the basin. Future temperature increases will be mostly due to the increased concentrations of greenhouse gases (mostly CO_2).

Importantly, the current study allows us to document the differences between the lake and land air temperature variations (Table 4). In 3 of the 10 data sets (five models for the two-time slices), increases in summer Tmax values over lakes are projected to be slightly greater than increases in Tmax values over land. However, in all experiments, increases in Tmax values over lakes are consistently lower than those of land areas and at greater ranges. Our findings from PRECIS simulations can be compared to previous in situ values observed in Great Lakes temperature changes, in which summer lake water temperatures increase more rapidly than regional air temperatures (Austin and Colman, 2007; O'Reilly et al., 2015). The disparity between these increases may seriously influence the communities and ecosystems of the Great Lakes region (Kling et al., 2003; Wuebbles et al., 2010; Gronewold et al., 2013). Mid-century and late century winter Tmin increases over lakes are consistently projected to be less than Tmin increases over land areas (Table 4). This is primarily due to ice cover reducing the turbulent fluxes and blocking the cooling of the air above the lake surfaces. However, the results show the late century winter Tmin (basin-wide, over lakes and lands) increases will be greater than the late century summer Tmax, indicating the effects of reduced Great Lakes ice cover may become more serious than they are at present.

We also examined and tabulated the environmental values in the grid cells over the lakes and over land separately (Table 4). The basin-wide mid-century numbers of extremely hot and cold days are projected to increase by 6.1 to 15.3 days and decrease by 3.9 to 6.2 days relative to the baseline period, respectively. Extreme changes will be greater in the late century, showing increases of 10.0 to 32.1 extremely hot days and decreases of 5.5 to 9.9 extremely cold days. Expected changes in the frequency of extremely hot and cold days over lakes are much less than those of over land. Furthermore, a much larger area (percentages) over the lakes than over the land will exhibit no increase in the number of days of extreme temperature (hot days and cold days) (Table 4). This is mostly due to the large heat capacity of lakes relative to the air over the surrounding land (Bonan, 1995; Scott and Huff, 1996). The expected increase in surface area of the lakes experiencing more extremely hot days in the future (7.2% to 12.7% in mid-century, 9.4% to 36.9% in the late century) is predicted to be less than the reduction in surface area of the lakes exhibiting fewer extremely cold days (39.1% to 77.5% in both mid-century and late century). Our findings are consistent with those of previously reported temperature differences over the Great Lakes (Scott and Huff, 1996; Austin and Colman, 2007; O'Reilly et al., 2015) and other recent climate change studies (Gula and Peltier, 2012; Notaro et al., 2015).

The projected number of mid-century and late century seasonal precipitation changes, very wet days (≥10 mm/day) and extremely wet days (≥40 mm/day) are plotted in Figs. 4 and 5. All other associated relevant information is presented in Table S4 and Table 5. The annual number of days of extreme precipitation will generally keep increasing from mid-century to late century; however, the distribution of precipitation changes will vary among seasons. The five experiments project future precipitation to increase the most during winter and spring. Furthermore, four of the five experiments project that summer precipitation will decline over the whole region while three experiments project future autumn precipitation to decrease over the whole region. These changes seem to be homogeneously distributed over lake and land areas (Fig. 4 and Table S4). The mid-century spatial extent of

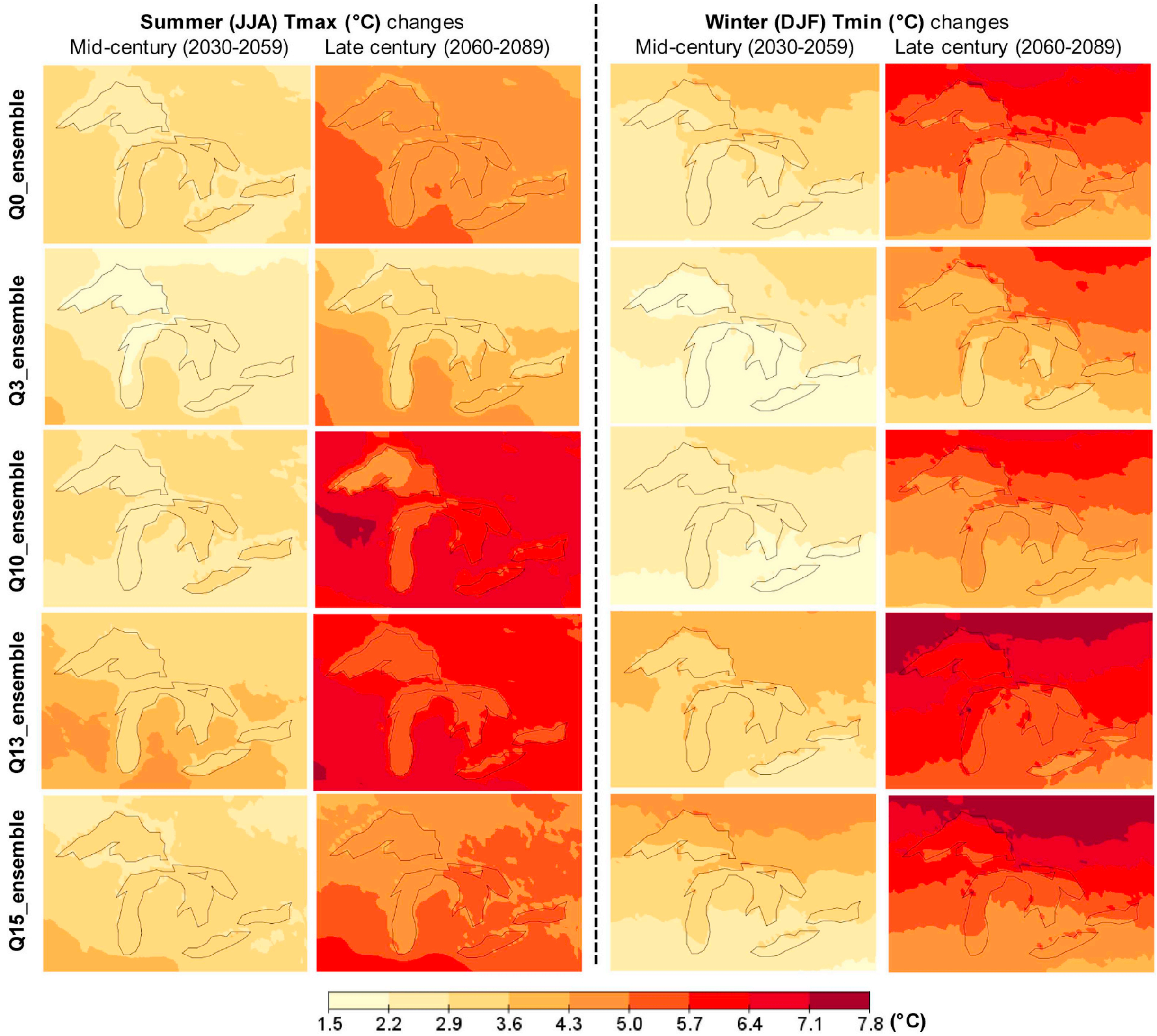

Fig. 2. Projected mid-century (2030–2059) and late century (2060–2089) summer Tmax and winter Tmin changes relative to the baseline period (1980–2009).

decreasing summer precipitation over the lake and land ranged between 6.7% to 89.7% and 15.9% to 75.9%, respectively. Similarly, late-century decreasing summer precipitation over the lake and land areas ranged from 22.5% to 98.1% and 32.3% to 99.5% (Table S4), respectively. Mid and late century autumn precipitation decreases are likely to be less pronounced than those of the summer season, but likely much higher than the changes in the winter and spring. Seasonal precipitation variation estimates in this study are similar to recent climate projections for this region by other GCMs and RCMs (Vavrus and Van Dorn, 2010; Notaro et al., 2015). However, our study adds a projected future decline in summer precipitation, which is noteworthy as a previous study reported that wetter springs would delay planting and promote early germination and emergence of corn and soybeans (Hellmann et al., 2008).

The number of mid-century and late century very wet days (≥10 mm/day) and extremely wet days (≥40 mm/day) of this region is shown to increase both over lake and land areas, but the increases are likely to be more intense over lakes than over land areas (Fig. 5 and Table 5). The increase in the annual frequency of mid-century very wet days relative to the baseline period for lake and land areas is projected to be 1.4 to 2.9 days and 0.7 to 2.5 days, respectively. Increases in the number of late-century very wet days may ultimately reach 3.9 days and 3.3 days per year, respectively. The numbers of mid-century and late century extremely wet days are shown to increase from 0.3 to 0.6 days and from 0.5 to 0.8 days over lake areas. Similarly, the number of mid-century and late century extremely wet days over land areas is projected to increase from 0.17 to 0.56 days and 0.51 to 0.76 days, respectively. The increasing number of very wet days (≥10 mm/day) and extremely wet days (≥40 mm/day) in this region may cause flooding (or severe snow events) in this region. Seasonal patterns show that the southwestern area may have spring flooding and drought events in the summer and autumn. This contrasts with the southeastern area, which may encounter increased rainfall or snow in the summer and winter. Additionally, the broad northeastern area of the region is likely to have more precipitation in autumn and winter (Fig. 5). Two of the five experiments (Q10 and Q13) indicate that 20% of the grid cells in this region are expected to experience fewer very wet days (≥10 mm/day) and extremely wet days (≥40 mm/day) in the future. These will be most likely to occur during summer; drought events appear in areas such as the southwest (southern Lake Superior and western Lake Michigan drainage basin) of the region (Fig. 5). Previously, Shrubsole et al. (1993) had reported historical flood events of this region occurred predominantly in March and April, and that the frequency of flood events increased between 1859 and 1987. Our projections indicate this region will continue to be subjected to more frequent and intensive flood events in the future. Overall, future precipitation and extreme day frequency changes in this region are very heterogeneous, varying from area to area and from season to season.

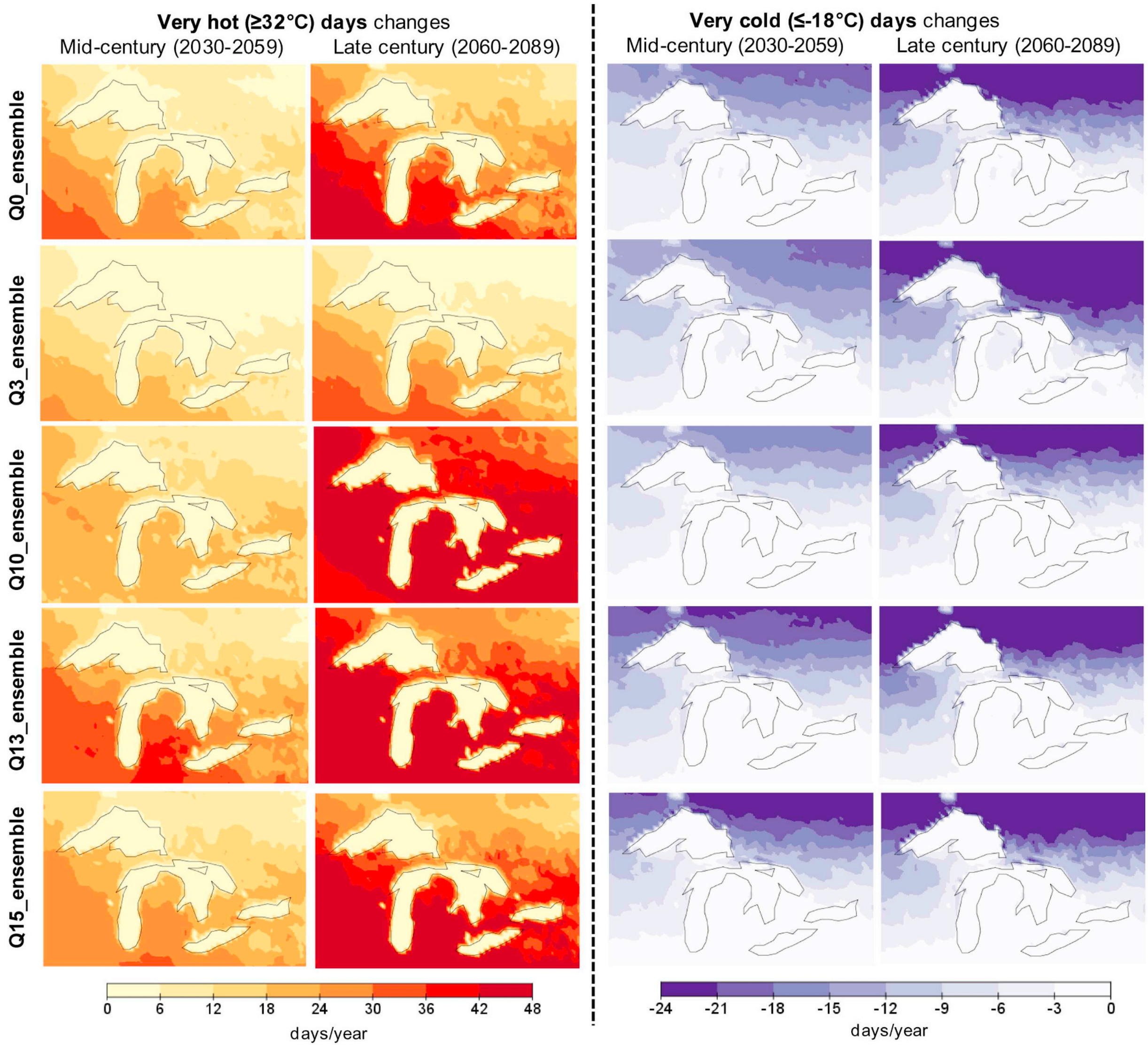

Fig. 3. Projected mid-century (2030–2059) and late century (2060–2089) yearly extreme hot (Tmax ≥32 °C) and extreme cold (Tmin ≤ −18 °C) days changes relative to the baseline period (1980–2009).

The anticipation of such variation will be an important consideration to enable jurisdictions to proactively plan means of mitigating the effects of future floods and droughts.

5. Conclusions

The results of this study suggest that PRECIS downscaling 5 HadCM3Q GCMs can effectively simulate future extreme climate events in the Great Lakes basin. Output data from the experiments compared favorably with observed data from 16 weather stations (1980–2009) distributed across the Basin adjacent to lakes and the surrounding landmass. The temperature and precipitation data validation comparisons between our study and those of other recent climate simulations this region indicated that consideration of land and lake areas together by certain single GCM (HadCM3Q GCMs) and RCM (PRECIS) perform comparably to models that use separate RCM downscaling over land and lake areas (e.g. Gula and Peltier, 2012; Notaro et al., 2015). Furthermore, the system used in this study, in which the lakes are modeled explicitly in the driving GCM and passed to the same RCM, may have advantages from the standpoint of models' compatibilities.

The projections show that mid-century (2030–2059) summer Tmax and winter Tmin for the region will rise by between 2.5 °C–3.5 °C and 2.4 °C–3.4 °C, respectively; while late century (2060–2089) summer Tmax and winter Tmin will increase by between 3.5 °C–5.9 °C and 4.3 °C–6.0 °C, respectively. The yearly number of mid-century and late century extremely hot (Tmax ≥32 °C) days are projected to increase by 6.1–15.3 days and 10.0–32.1 days, respectively; whereas the yearly number of extremely cold (Tmin ≤ −18 °C) days will decrease by 3.9–6.2 days (mid-century) and 5.5–9.9 days (late century). The spatial distribution of changes in temperature patterns indicates that Tmax increases over the southern part of this region (US side) will be greater than the northern part (Canadian side), yet the winter Tmin pattern increases are projected to be converse to the Tmax pattern in this region. Importantly, our study examines land and lakes areas separately for extremely hot and cold days. Results indicate that most grid cells of lake areas (up to 90%) will not change in terms of the numbers of extremely hot days.

This study indicates that the summer air temperatures over the Great Lakes may increase faster than those over the surrounding land areas, and this tendency may extend into the late century. Our projected findings for this region predict greater increases in temperatures over lake areas than over land areas, which are consistent with previous in situ studies (Scott and Huff, 1997; Austin and Colman, 2007; O'Reilly et al., 2015). Future precipitation in the region is projected to rise

Table 4
Projected mid-century (2030–2059) and late century (2060–2089) changes in summer Tmax, winter Tmin, and the number of very hot (≥32 °C) day and very cold (≤ −18 °C) day changes relative to the baseline period (1980–2009). “Basin” and “Land” refer to the “basinwide dataset” and “Land-only dataset”, respectively.

		Summer (JJA)			Mean yearly very hot (≥32 °C) days											
		Tmax (°C) increase			Unchanged area (%)			Increased area (%)			Increased days			Overall increased days		
		Basin	Lake	Land	Basin	Lake	Land	Basin	Lake	Land	Basin	Lake	Land	Basin	Lake	Land
2030–2059	Q0	2.99	3.07	2.96	27.3%	92.8%	3.3%	72.7%	7.2%	96.7%	13.2	13.3	13.2	9.6	1.0	12.8
2030–2059	Q3	2.46	2.21	2.56	27.2%	92.6%	3.3%	72.8%	7.4%	96.7%	8.4	8.9	8.4	6.1	0.7	8.1
2030–2059	Q10	2.86	2.88	2.85	25.7%	87.3%	3.1%	74.3%	12.7%	96.9%	15.7	9.1	16.0	11.7	1.2	15.5
2030–2059	Q13	3.49	3.18	3.61	25.9%	88.2%	3.1%	74.1%	11.8%	96.9%	20.7	13.2	21.0	15.3	1.6	20.4
2030–2059	Q15	3.12	3.28	3.06	26.6%	90.6%	3.2%	73.4%	9.4%	96.8%	17.5	13.6	17.6	12.8	1.3	17.0
2060–2089	Q0	4.60	4.56	4.61	26.1%	89.0%	3.1%	73.9%	11.0%	96.9%	24.4	16.3	24.8	18.1	1.8	24.0
2060–2089	Q3	3.54	3.32	3.62	26.6%	90.6%	3.1%	73.4%	9.4%	96.9%	13.7	11.3	13.7	10.0	1.1	13.3
2060–2089	Q10	6.24	5.47	6.52	18.8%	63.1%	2.5%	81.2%	36.9%	97.5%	39.5	8.7	43.8	32.1	3.2	42.6
2060–2089	Q13	5.94	5.45	6.12	18.8%	63.3%	2.4%	81.2%	36.7%	97.6%	36.1	8.2	39.9	29.3	3.0	38.9
2060–2089	Q15	4.98	5.00	4.97	23.4%	79.1%	3.1%	76.6%	20.9%	96.9%	32.0	11.5	33.6	24.5	2.4	32.6

		Winter (DJF)			Mean yearly very cold (≤ −18 °C) days changes											
		Tmin (°C) increase			Unchanged area (%)			Increased area (%)			Decreased days			Overall decreased days		
		Basin	Lake	Land	Basin	Lake	Land	Basin	Lake	Land	Basin	Lake	Land	Basin	Lake	Land
2030–2059	Q0	3.00	2.81	3.07	11.7%	42.4%	0.4%	88.3%	54.9%	99.6%	6.0	1.1	7.0	−5.2	−0.6	−6.9
2030–2059	Q3	2.27	2.00	2.37	6.3%	22.5%	0.3%	93.7%	77.5%	99.7%	6.6	1.2	8.2	−6.2	−1.0	−8.1
2030–2059	Q10	2.43	2.35	2.46	17.0%	60.9%	1.0%	83.0%	39.1%	99.0%	4.7	1.0	5.3	−3.9	−0.4	−5.2
2030–2059	Q13	3.43	3.22	3.51	15.0%	53.2%	1.1%	85.0%	46.8%	98.9%	6.9	1.3	7.9	−5.8	−0.6	−7.8
2030–2059	Q15	3.44	3.34	3.48	13.9%	50.8%	0.4%	86.1%	49.2%	99.6%	6.7	1.0	7.7	−5.8	−0.5	−7.7
2060–2089	Q0	5.11	4.91	5.19	12.2%	44.1%	0.5%	87.8%	55.9%	99.5%	8.1	1.3	9.5	−7.1	−0.7	−9.4
2060–2089	Q3	4.33	3.80	4.52	6.3%	22.5%	0.3%	93.7%	77.5%	99.7%	10.6	1.8	13.1	−9.9	−1.4	−13.0
2060–2089	Q10	4.79	4.67	4.84	17.0%	60.9%	1.0%	83.0%	39.1%	99.0%	6.6	1.3	7.4	−5.5	−0.5	−7.3
2060–2089	Q13	5.98	5.67	6.09	15.0%	53.2%	1.1%	85.0%	46.8%	98.9%	8.7	1.5	10.0	−7.4	−0.7	−9.9
2060–2089	Q15	5.76	5.44	5.87	13.9%	50.8%	0.4%	86.1%	49.2%	99.6%	8.0	1.2	9.2	−6.8	−0.6	−9.1

Note: the unchanged and decreased area (%) of very cold days were very similar between mid-century and late century (lower panel), they were not transcription errors and might due to limitation of those extremely cold areas in this region.
“Unchanged area (%)” → “Projected to be unchanged area (%)”.
“Increased area (%)” → “Projected to be increased area (%)”.
“Increased days” → “Projected to be increased days compared to the baseline period”.
“Overall increased days” → “the overall projection increased days compared to the baseline period”.

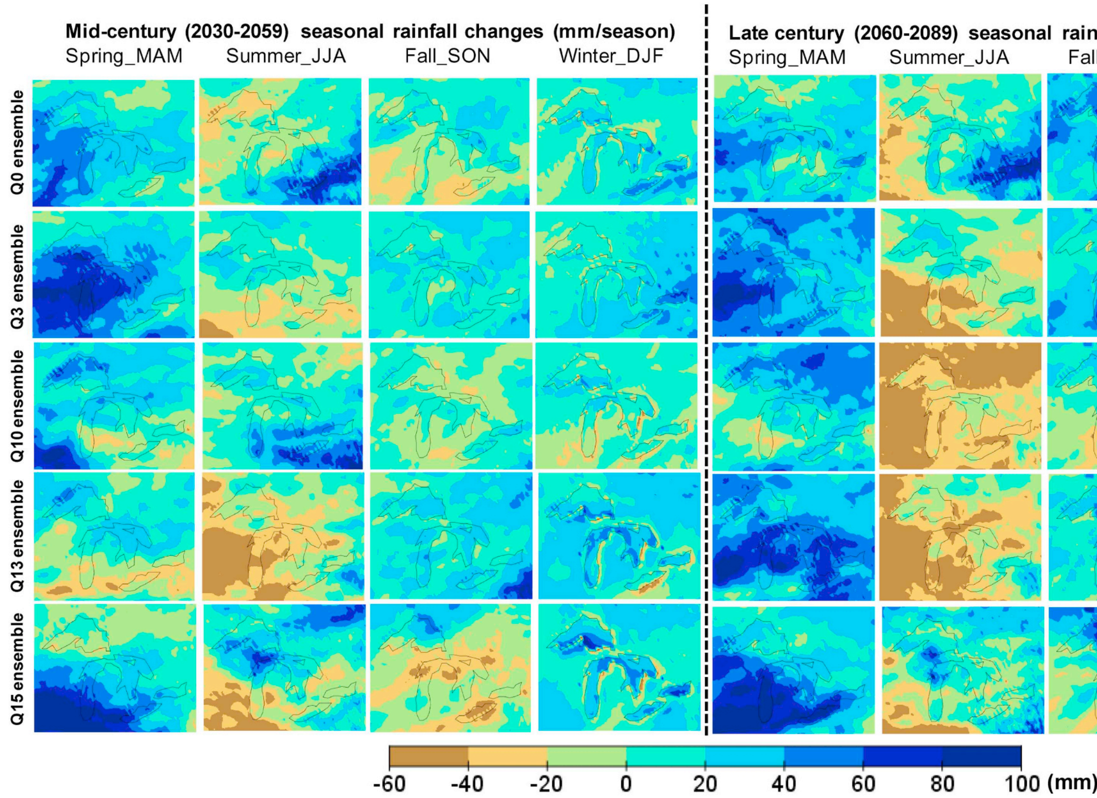

Fig. 4. Projected mid-century (2030–2059) and late century (2060–2089) seasonal precipitation (mm/season) changes relative to the baseline period (1980–2009).

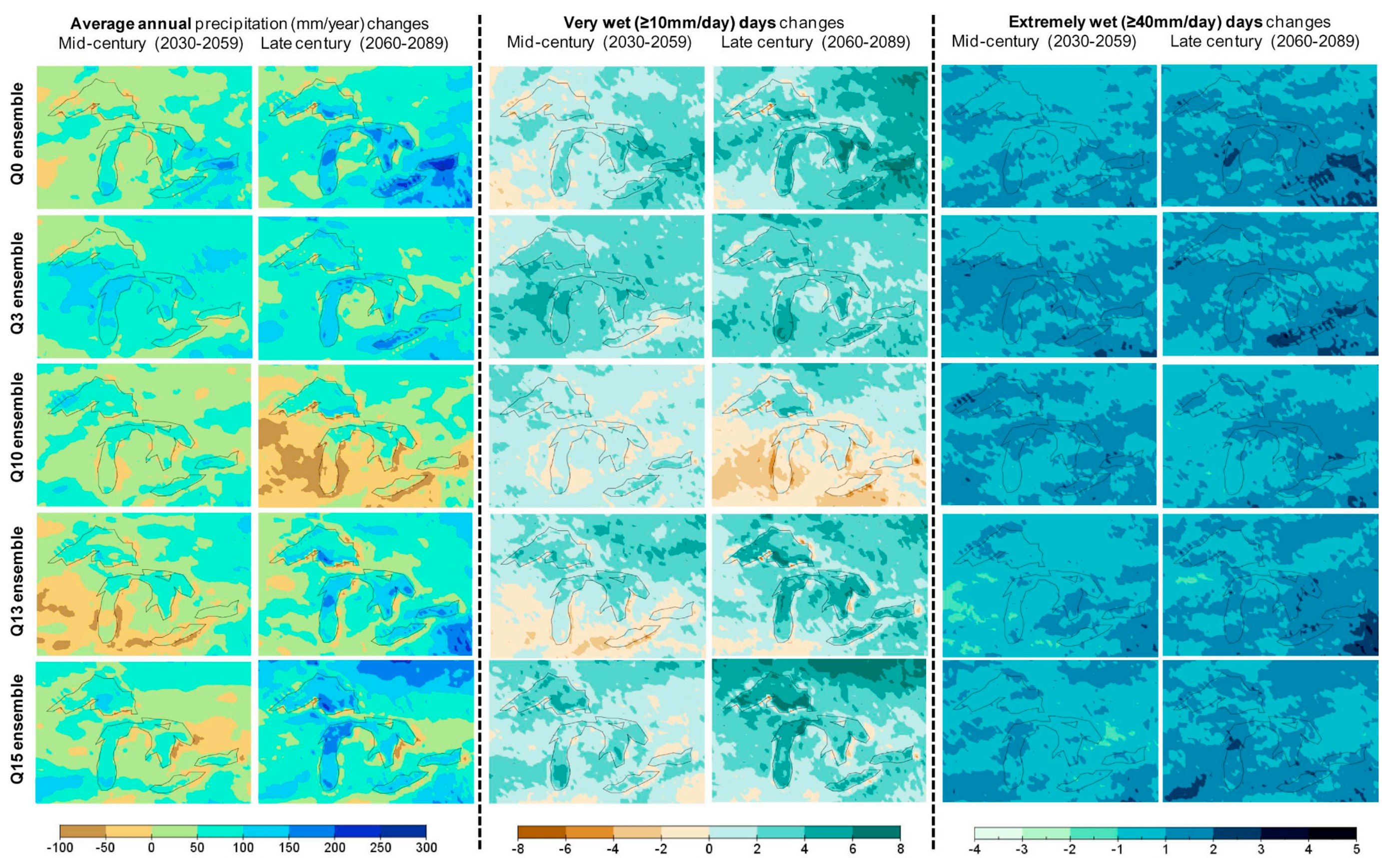

Fig. 5. Projected mid-century (2030–2059) and late century (2060–2089) annual precipitation (mm/year), very wet days (≥ 10 mm/day) and extreme wet days (≥ 40 mm/day) changes relative to the baseline period (1980–2009).

Table 5
Projected mid-century (2030–2059) and late century (2060–2089) changes in the annual number of very wet (≥10 mm/day) and extremely wet (≥40 mm/day) days relative to the baseline period (1980–2009). Other information as described in Table 4.

		Very wet (≥10 mm/d) days changes														
		Decreased area (%)			Decreased days			Increased area (%)			Increased days			Overall increased days		
		Basin	Lake	Land	Basin	Lake	Land	Basin	Lake	Land	Basin	Lake	Land	Basin	Lake	Land
2030–2059	Q0	6.7%	6.7%	7.0%	0.77	0.60	0.84	93.0%	92.8%	93.0%	2.17	2.24	2.15	1.96	2.03	1.94
2030–2059	Q3	2.6%	2.4%	2.8%	0.90	0.66	0.98	97.3%	97.6%	97.2%	2.70	2.97	2.60	2.60	2.89	2.50
2030–2059	Q10	18.4%	6.7%	24.1%	0.64	0.54	0.64	80.5%	92.8%	75.9%	1.25	1.55	1.11	0.89	1.40	0.70
2030–2059	Q13	21.7%	12.0%	26.0%	1.15	1.09	1.16	77.7%	87.5%	74.0%	2.09	2.13	2.09	1.38	1.73	1.25
2030–2059	Q15	10.4%	3.8%	13.8%	0.65	0.79	0.63	88.9%	96.2%	86.2%	1.88	2.74	1.52	1.60	2.60	1.23
2060–2089	Q0	2.3%	0.5%	3.1%	1.61	1.42	1.62	97.6%	99.5%	96.9%	3.56	3.99	3.40	3.44	3.96	3.25
2060–2089	Q3	1.7%	0.7%	2.2%	0.92	1.00	0.91	98.2%	99.3%	97.8%	2.75	3.47	2.49	2.69	3.43	2.41
2060–2089	Q10	45.3%	33.3%	49.9%	1.57	1.22	1.65	54.4%	66.2%	50.1%	1.44	1.65	1.34	0.08	0.69	−0.15
2060–2089	Q13	6.1%	1.9%	7.7%	1.40	1.58	1.39	93.9%	98.1%	92.3%	2.98	4.06	2.55	2.71	3.95	2.25
2060–2089	Q15	4.8%	1.0%	6.6%	1.06	0.90	1.07	94.8%	98.8%	93.4%	3.19	4.31	2.76	2.98	4.25	2.51

		Extremely wet (≥40 mm/d) days changes														
		Decreased area (%)			Decreased days			Increased area (%)			Increased days			Overall increased days		
		Basin	Lake	Land	Basin	Lake	Land	Basin	Lake	Land	Basin	Lake	Land	Basin	Lake	Land
2030–2059	Q0	7.0%	8.9%	6.4%	0.16	0.16	0.15	91.8%	89.7%	92.6%	0.46	0.43	0.48	0.41	0.38	0.43
2030–2059	Q3	5.0%	9.4%	3.4%	0.13	0.15	0.12	93.9%	88.2%	96.0%	0.60	0.64	0.58	0.55	0.55	0.56
2030–2059	Q10	7.4%	10.1%	6.5%	0.18	0.20	0.16	92.0%	89.7%	92.9%	0.58	0.64	0.56	0.52	0.56	0.51
2030–2059	Q13	20.2%	15.8%	21.7%	0.23	0.22	0.23	77.5%	81.8%	75.9%	0.44	0.38	0.46	0.29	0.28	0.30
2030–2059	Q15	24.3%	16.3%	27.1%	0.25	0.18	0.27	72.3%	80.1%	69.7%	0.37	0.41	0.35	0.20	0.30	0.17
2060–2089	Q0	1.4%	0.7%	1.7%	0.11	0.06	0.12	97.8%	98.6%	97.6%	0.80	0.85	0.78	0.78	0.84	0.76
2060–2089	Q3	2.0%	1.4%	2.2%	0.16	0.07	0.19	97.6%	98.3%	97.4%	0.73	0.76	0.73	0.71	0.74	0.70
2060–2089	Q10	7.7%	7.4%	7.8%	0.14	0.18	0.13	90.8%	91.6%	90.5%	0.56	0.52	0.58	0.50	0.47	0.52
2060–2089	Q13	3.9%	2.9%	4.3%	0.15	0.15	0.15	94.8%	94.7%	94.9%	0.69	0.67	0.70	0.65	0.63	0.66
2060–2089	Q15	7.1%	2.4%	8.8%	0.16	0.10	0.17	91.6%	96.9%	89.7%	0.60	0.65	0.58	0.54	0.63	0.51

"Decreased area (%)" → "Projected to be decreased area (%)".
"Decreased days" → "Projected to be decreased days compared to the baseline period".
"Increased area (%)" → "Projected to be increased area (%)".
"Increased days" → "Projected to be increased days compared to the baseline period".
"Overall increased days" → "the overall projection increased days compared to the baseline period".

between by 29–73 mm/year (2030–2059) and 14–91 mm/year (2060–2089) relative to the baseline period (1980–2009). The distribution of these changes will vary season by season, however. Future spring and winter precipitation will increase intensively, and autumn precipitation will increase but less so than for spring. Future summer precipitation will decrease relative to 1980–2009. Our study also predicts the number of very wet days (≥10 mm/day) and extremely wet days (≥40 mm/day) to increase into mid-century and continue increasing into the late 21st century. The predicted increase in numbers of wet days over lake areas is greater than that predicted to occur over land areas. Furthermore, analysis of projections for the individual grid cells indicated that about 20% of the area over both lake and land areas may suffer fewer wet days (≥10 mm/day and ≥ 40 mm/day) compared to the baseline period.

Overall, our study has identified three aspects of regional climate change that should be considered in the Great Lakes Basin, or other areas that encompass large water and land bodies: (1) distinguishing climate change differences between lake (water) and land areas; (2) addressing differences in seasonal variations; (3) documenting the spatial distribution of sub-areas in which climate change variables are likely to be pronounced (decreases and/or increases) and those in which little change will occur. Identifying the distribution of these spatial and temporal variations may be especially useful in assessing local and regional risks of temperature extremes, floods, and droughts, from which climate adaptation strategies can be implemented to minimize the disasters caused by extremes events.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2018.10.019.

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